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PRINCIPLES OF A NEW PORTABLE ELECTROMETER

By Ross Gunn
Naval Research Laboratory, Washington, D.C.

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Abstract

The fundamental principles underlying the operation of a new type of portable electrometer are given. It is shown that the periodic transfer of static charges from one capacity system to another and back again can be used to produce an alternating electrical potential. The alternating potential is amplified by means of vacuum tubes, then rectified by a synchronous commutator and the resulting direct current used to operate an indicator. Instruments with capacities of about 25 cm and sensitivities of 10^4 microamperes per volt have been built to operate with portable microammeters used as the indicator. The period of the device depends on the indicator employed and is small.

A TRULY portable and sensitive electrometer might be very useful to industry as well as to the laboratory physicist if it could be made sufficiently rugged to withstand the severe treatment to which most commercial instruments are subject. The use of ordinary suspension type laboratory instruments on shipboard is quite impossible and in certain problems it has been necessary to develop a sensitive electrostatic instrument which is sufficiently rugged to use either on shipboard or on aircraft. In this paper we give the underlying principles of the device which are believed to be new and describe one of the early models of a practical instrument.

The instrument we shall describe has been developed to replace the widely advertised vacuum tube type of electrometer, because of certain difficulties encountered in its general application. The vacuum tube device, primarily because of its simplicity, is quite satisfactory in an isolated laboratory where shielding of the entire system, galvanometer and special batteries is practical but the tube is especially susceptible to radio interference and in ordinary service many difficulties arise. Moreover, its voltage sensitivity is not great when used with ordinary portable indicating meters and its leakage resistance is not a constant.

With the exception of the vacuum tube electrometer, all the usual electrostatic devices employ light suspended mechanical systems which are acted on by electrostatic charges. Evidently these light suspended systems make such instruments commercially impractical and while the new device is not yet superior in sensitivity to a sensitive quadrant electrometer like the Compton instrument, it can undoubtedly be made so, and has the added advantage of complete portability. The new instrument is a true electrometer and the charges placed on the semicylinders are free of all leakage effects, save only the usual small leakage through the amber supports and through the surrounding air. By evacuating the cylindrical system the latter leakage may be avoided.

PRINCIPLE

The underlying principle of the new instrument may be understood from a consideration of the simplified circuit of Fig. 1. In this circuit the capacity C_1 represents a fixed capacity of the system upon which is placed an unknown charge q_0. The capacity of the condenser C_2 is made periodic and takes on all values from zero to C_2'. Initially when the charge q_0 is on C_1, C_2 is zero but as C_2 is increased the condenser C_1 shares its charge with C_2 and a charge flows through the wires that connect the condensers and hence through the inserted resistance R. The current through the resistance sets upon a potential difference across R which can be measured or amplified by a vacuum tube, *V. T.* As soon as the capacity of the condenser C_2 starts to decrease in value, the current through R is reversed and the charge flows back into C_1. The system constantly strives to reach the static state in which the charges are divided in proportion to the capacity but this condition is never attained because C_2 constantly changes with time.

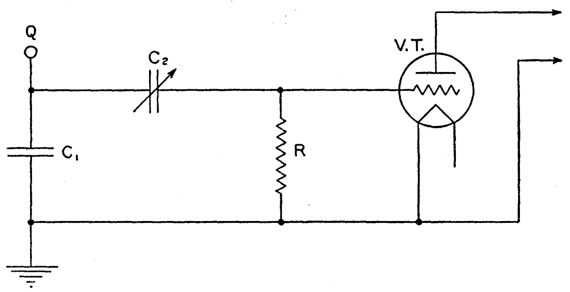

Fig. 1. Simplified circuit diagram.

It is to be especially noted that after C_1 had returned to its original zero capacity, the entire initial charge q_0 is back on the condenser C_1 and the interchange of charge between the two condensers has added or subtracted nothing to the electrical energy because the energy dissipated in the resistance R was supplied by the mechanical forces which make C_2 periodic. The net result of the interchange of charge between the two condensers is an alternating potential across R of a frequency equal to that of the variation of C_2 and this potential is proportional to the original static charge. Thus the circuit may be adopted for measurement of static charge by simply indicating the magnitude of the alternating potential difference. Moreover, since the generated potential is alternating it may readily be amplified a great many times and the sensitivity can undoubtedly be pushed up to a point over a hundred times that already attained.

If at the time $t=0$, we take $C_2=0$ and $q_1=q_0$ then the circuital relations lead to the integral equation

$$\frac{q_0}{C_1} - Ri - \frac{\dfrac{C_1}{C_2}+1}{C_1}\int i\,dt = 0 \qquad (1)$$

where i is the current through the resistance R and q_0 is the initial charge on C_1. This equation is not readily solved except by approximation because C_2 changes with time. We choose to solve Eq. 1 for the potential E applied to the grid of the vacuum tube and leave it in the integral form. Thus

$$E = \frac{q_0}{C_2}\left[\frac{q_1}{q_0}\left(1 + \frac{C_2}{C_1}\right) - 1\right] \tag{2}$$

where q_1 is the instantaneous charge on C_1. In the steady state it is evident from Eq. 2 that E will be zero but as C_2 changes periodically as the result of mechanical forces E will become finite and periodic with C_2. We can see without analysis that the potential E across R will increase as dq/dt increases and therefore at low frequencies will be approximately proportional to the frequency of the variation of C_2. However, when the frequency approaches the relaxation frequency of the circuit the condenser systems have insufficient time to completely charge or discharge and E drops. In general, the maximum E for a given applied charge q_0 occurs when the frequency of the change in C_2 is slightly less than f_s the effective relaxation frequency of the circuit. Thus

$$f_r = 1 + \frac{C_1}{\bar{C}_2} \Big/ RC_1 \tag{3}$$

where $\bar{C}_2$ is a mean value of the periodically variable capacity of the condenser C_2. The requirement in regard to the driving frequency need only be met when maximum sensitivity is desired.

METHOD

The potential applied to the grid of the first vacuum tube is undoubtedly of very complicated wave form but it will necessarily have a strong component of the fundamental frequency at which C_2 is varied. This fundamental alternating potential can be amplified and, by rectification at the output by an electron tube or by a copper oxide rectifier, can be made to operate a sensitive portable direct current instrument.

Such a method was used initially but it proved to be entirely unsatisfactory because: (1) amplifier noises are rectified equally with the impressed signal and the indicating meter measures these; (2) the arrangement is incapable of distinguishing the sign of the charge q_0. In the special problem for which the instrument was designed it was necessary to know both the magnitude and the sign of the unknown change, and a new system has been devised to attain this goal.

It is well known that vacuum tube amplifiers are poorly adapted for the amplification of steady potentials so we have avoided their use in this manner by a special system which is applicable to a great many electrical problems. Starting with a steady potential we convert this into an alternating potential, as in the case described above, by a special inverter unit. The resulting alternating potential is amplified to any desired degree, by suitable arrays of vacuumtubes, and instead of measuring the resulting a. c. potential directly, it is passed through a converter operating in strict synchronism with the inverter unit. This rectifies the output a.c. and it is led directly to a direct current indicator. It is evident that a reversal in sign of the applied potential will reverse the phase of the amplified a.c. and the direct current indicator will reverse its sign. Thus the arrangement is capable of not only measuring the magnitude of the applied potential but also its sign. The system has other valuable properties; for example, fluctuations in the amplifier or a moderately high noise level due to microphonic effects will not appreciably affect the indicator because the indicator obviously responds only to the inverter-converter frequency. The amplification per stage can therefore be carried to quite high values. Synchronous mechanical rectifiers are highly efficient and, aside from their occasional erratic operation due to the poor condition of the contacts, are quite satisfactory. It is to be noted that the indicating meter and the control mechanism may be readily placed at any desired distance from the electrometer proper which permits the device to be installed in inaccessible positions. In certain applications this is of considerable importance.

An Instrument

The general design of an early model is shown in Fig. 2, in which 1 represents the driving motor of sufficient power to drive the inverter-converter unit at a constant speed. Semicylindrical electrodes 4 and 5 take the place of the usual quadrants and one of them (4) is highly insulated by means of amber. The semi-cylindrical inductors 6 and 7 revolve inside the electrodes and are suitably spaced from them. The inductors are connected to the input of a vacuum tube amplifier 8, 9 and 10 and the alternating current induced in them, due to the presence of static charges on the electrodes, is amplified and passed through a converter unit 3 by way of an output transformer 11.

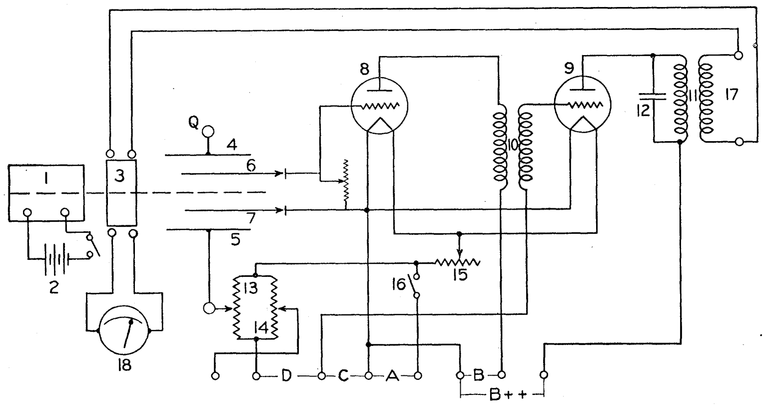

Fig. 2. General design of an early model.

The inverter and converter units are driven by the same shaft and therefore the current delivered to the indicator 18 is always direct current. The converter unit is simply a two segment copper commutator, each segment being connected to a ring. The brush assembly is capable of being shifted about the axis of rotation to permit the proper adjustment of phase. A potentiometer 13 is provided to adjust properly the potential of one semicylindrical electrode and a magnetic switch is used to bring the electrode 4 to the potential of 5 during periods of adjustment. Suitable batteries are connected to the system as indicated in the diagram.

Except under unfavorable conditions it has been only necessary to shield and ground the inverter unit together with the lead to the first grid. All battery and meter leads of ordinary twisted conductor have been run whereever necessary without shielding.

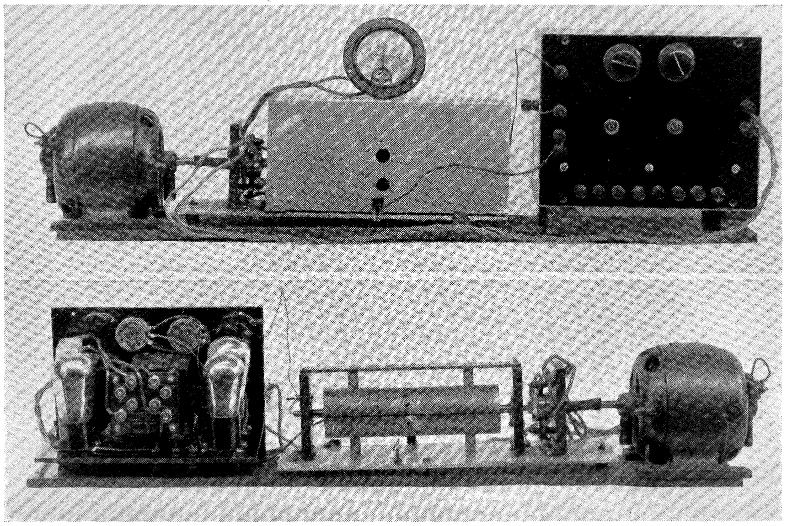

Fig. 3. Photographs of complete instrument.

SENSITIVITY

The sensitivity of the electrometer may be varied over any desired range by simply changing the magnitude of the resistance between the inductors 6 and 7. The instrument shown can be operated at any sensitivity up to about 10,000 microamperes per volt. A slight fluctuation of the indicating meter, due to commutation, amounting to about one microampere limits the effective voltage sensitivity with portable instruments to about 10^{-4} volts. Higher sensitivity can undoubtedly be secured by paying closer attention to details of construction and increasing the overall amplification.

The capacity of the electrometer can be controlled over a moderate range. The one described above had a capacity of 44 centimeters and therefore its useful quantity sensitivity with portable instruments was 4×10^{-15} coulomb per microampere. Experience with the device indicates that instruments with capacities as low as 10 cm could be built without sacrificing the voltage sensitivity indicated above.

The period of the instrument depends on the meter used as an indicator and is small.

CONCLUSION

The difficulties encountered in the development of the instrument have been largely those of mechanical design. Present instruments are satisfactory and retain their calibration over considerable periods of time. It is necessary to clean occasionally the converter unit and check the over-all gain of the amplifier to insure the stability of the zero. We have not attempted to push the sensitivity of the instrument to its logical limit, about 100 times greater, because there has been no need for such high sensitivities. The present device is comparable in sensitivity to a Compton electrometer in stable adjustment, yet is completely portable and sufficiently rugged to be used in aircraft.

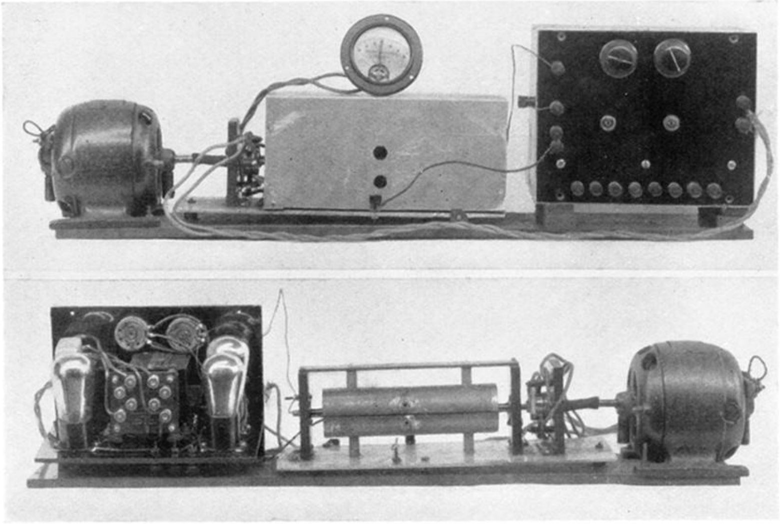

Fig. 3. Photographs of complete instrument.